A U.S.-based Electron-Ion Collider

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Outline:

- EIC: goals, fundamental problems, main parameters
- Key experiments of EIC physics program
- EIC realization: eRHIC and JLEIC
- Status of EIC project

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Electron-Ion Collider: goals

Electron-Ion Collider in USA is the project of a new collider of polarized electrons and ions on the base of RHIC@BNL (eRHIC) or CEBAFa@JLab (JLEIC).

• To provide continuity of the U.S. high-energy nuclear physics program after 2025, when RHIC II and JLab@12 GeV will complete their programs.

• To unite RHIC and JLab users and attract the international community.

• To have a facility to test new concepts and technologies in accelerator physics.

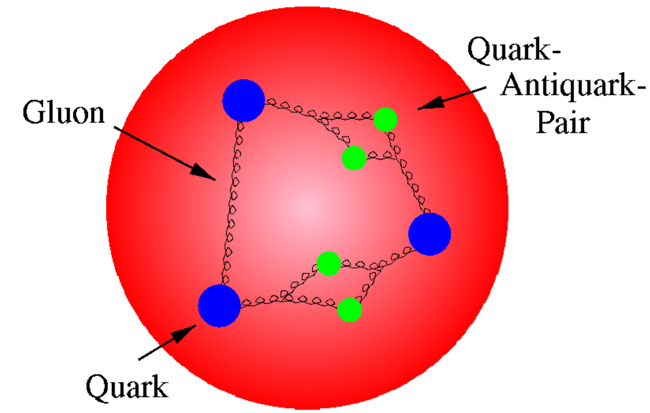
• To answer a central question of nuclear physics on the nature of visible matter around us: **How do quarks and gluon form nucleons and nuclei?**

• To expand kinematic boundaries and precision of planned measurements: EIC should be a discovery and precision machine and a world-leading facility to study Quantum Chromodynamics (QCD).

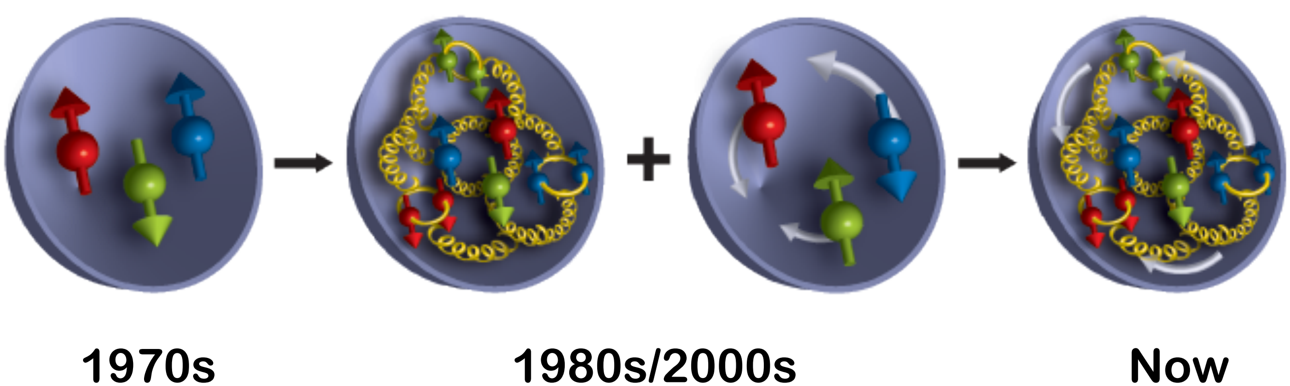
EIC: fundamental problems

- **Proton mass puzzle**: current quarks of the QCD Lagrangian carry ~10% of the proton mass. What is the role of quark-anquark quantum fluctuations and gluons?

$$\mathcal{L}_{QCD} = \bar{\psi}_i (i(\gamma^\mu D_\mu)_{ij} - m\delta_{ij})\psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

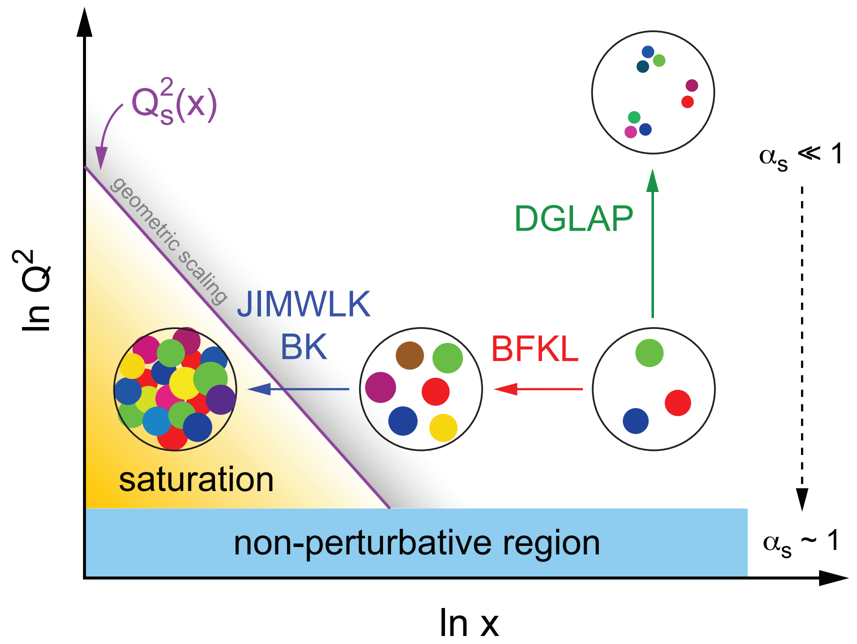


- **Proton spin puzzle**: quarks carry ~30% of the proton spin. What is the role of gluons and parton orbital motion? How are quarks and gluons distributed in coordinate and momentum space?

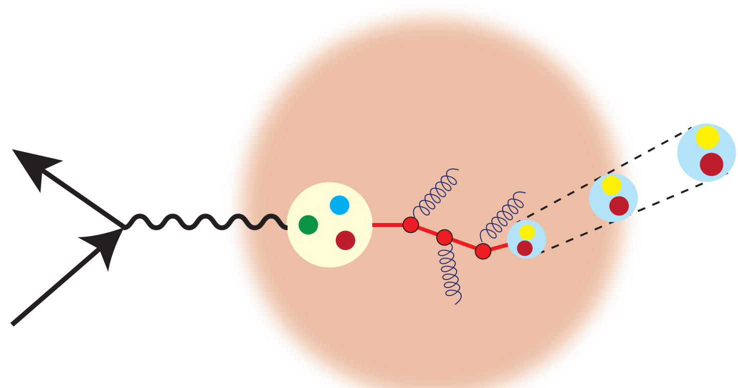


EIC: fundamental problems (2)

• **Gluon density in nuclei at high energies**: How does nuclear matter effect the gluon density? Does gluon saturation take place at high gluon density and what are its properties?



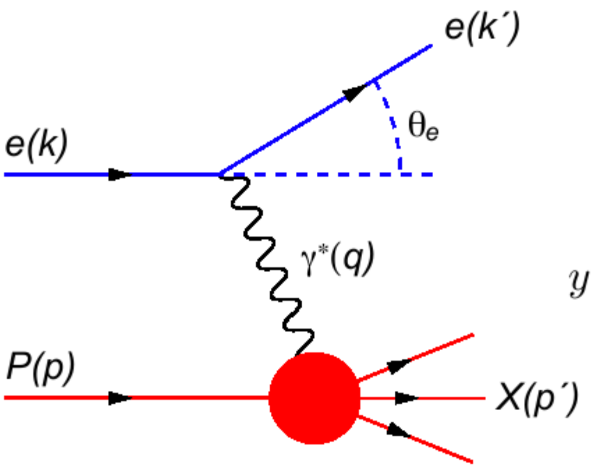
• **Nature of hadronization and confinement**: How do fast color changes interact with nuclear medium?



- important for heavy ion physics
- EIC allows us to control the photon energy and the size of nuclear matter

EIC: "QCD microscope"

- The cleanest way to study microscopic structure of hadrons is to use deep inelastic scattering (DIS):



$$Q^2 = -q^2 = -(k-k')^2$$

$$Q^2 = 4E_e E'_e \sin^2\left(\frac{\theta'_e}{2}\right)$$

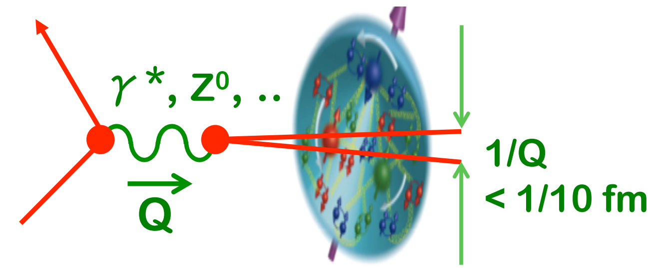
Measure of resolution power or "Virtuality"

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

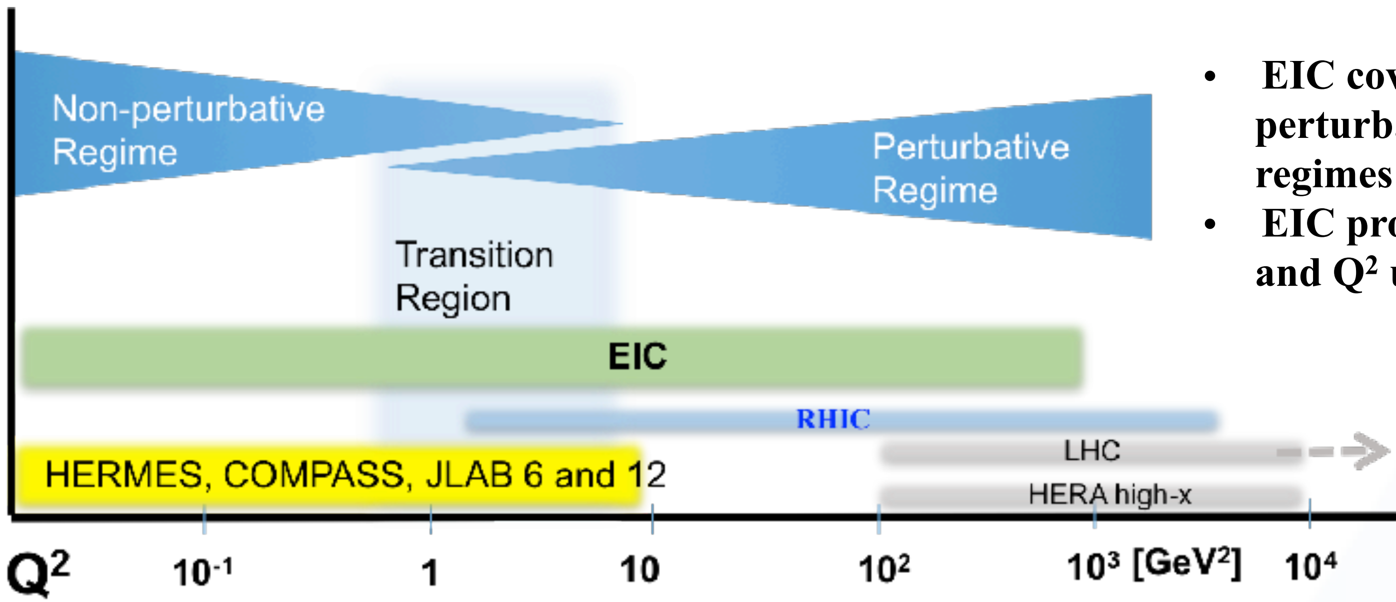


$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

- Main characteristics and advantages:
  - point-like probe → clean theoretical description and interpretation
  - control over parton kinematics
  - possibility to study semi-inclusive and exclusive (elastic) final states → 3D parton structure.

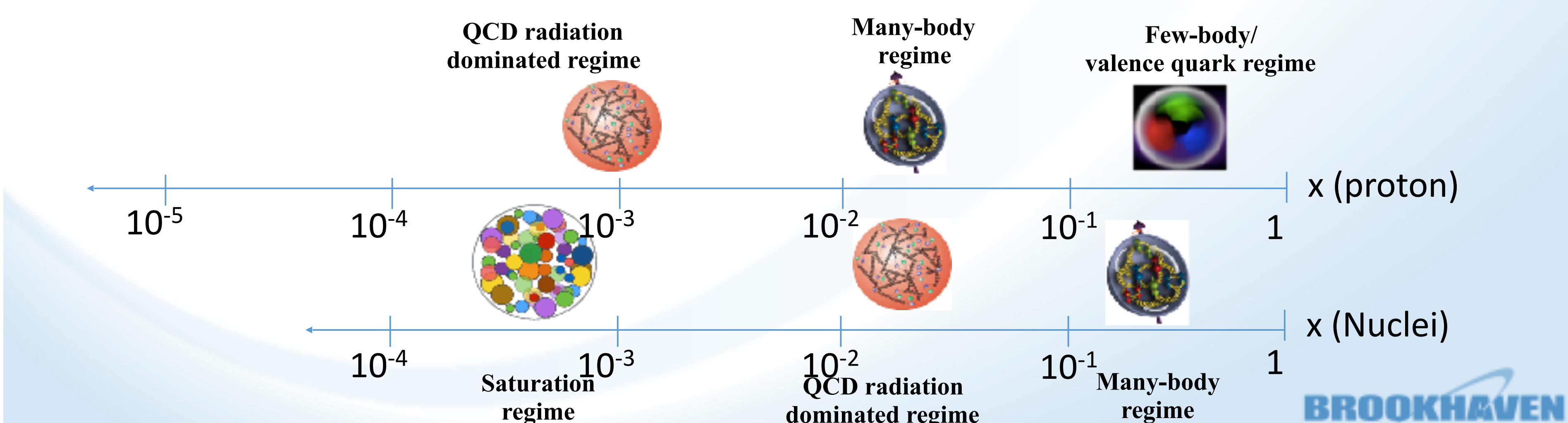
Main EIC parameters: energy

- Center of mass energy $\sqrt{s}$ ~20-100 GeV, possibility to increase up to $\sqrt{s}$ ~150 GeV → opens wide coverage in Q^2 and x.



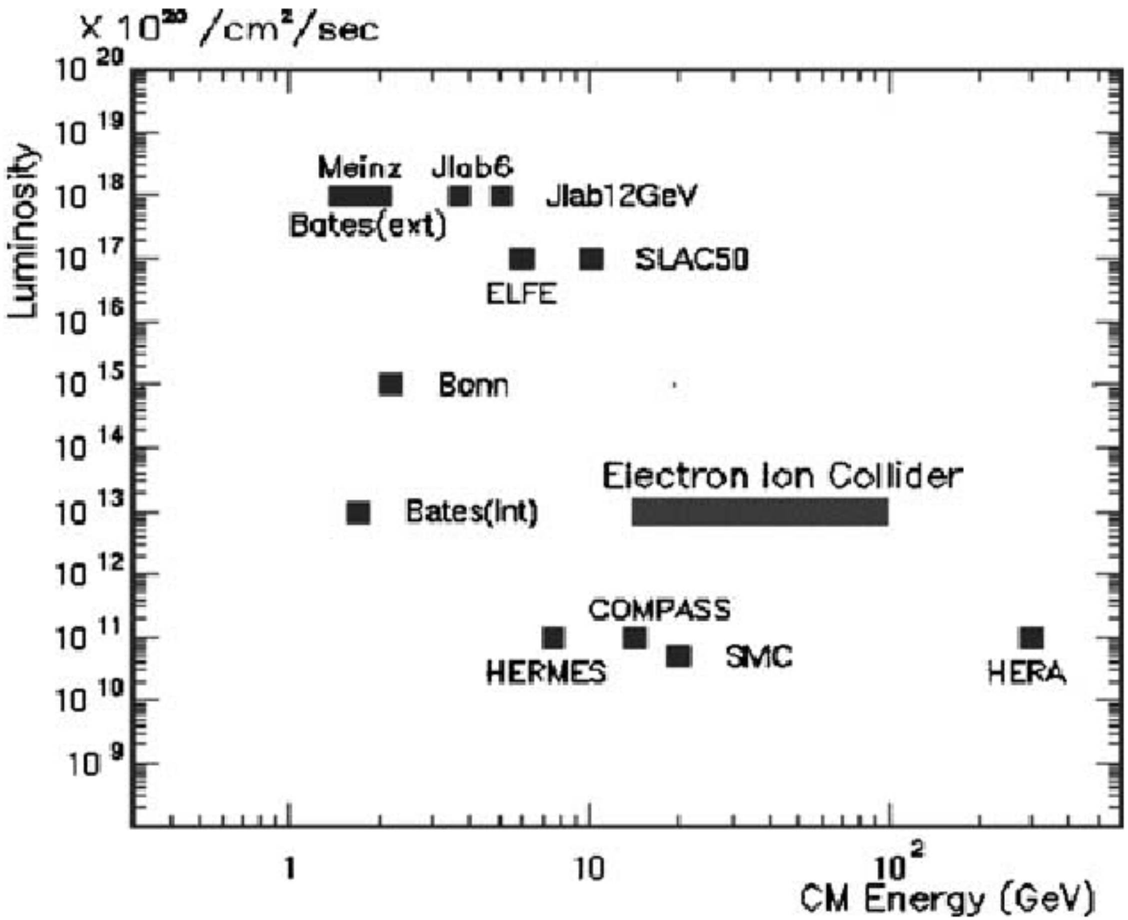
- EIC covers non-perturbative, perturbative and transition regimes
- EIC provides long evolution range and Q^2 up to ~1000 GeV² (0.01 fm)

Going from large to small x nucleons and nuclei reveal their full structure

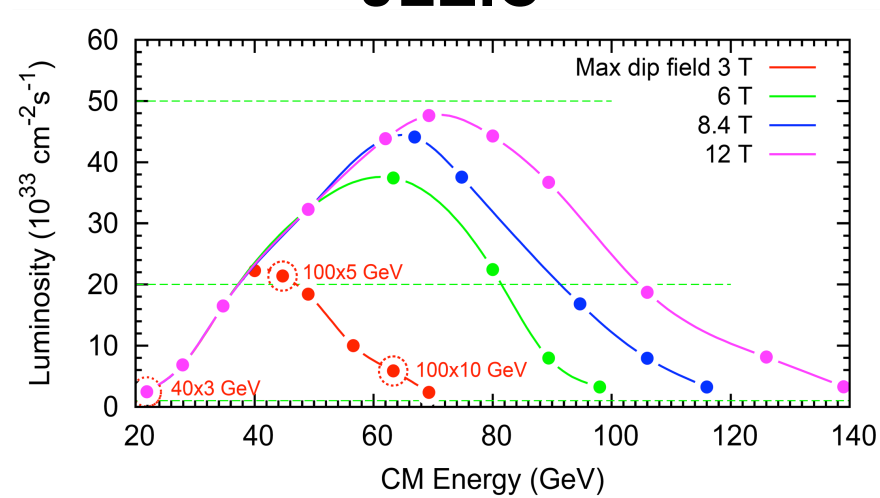


Main EIC parameters: luminosity

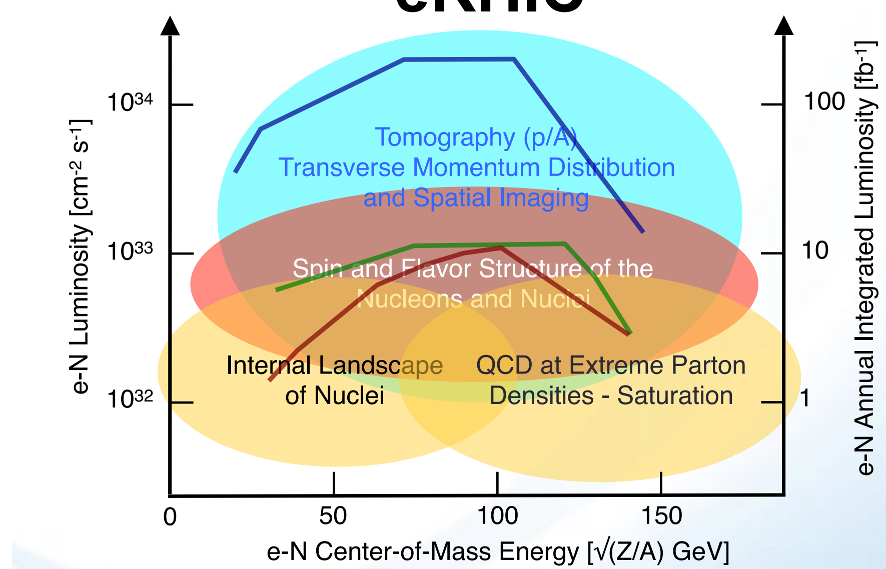
• High luminosity $10^{33\text{-}34}$ $sm^{-2}s^{-1}$ → precision measurement of semi-inclusive and exclusive processes.



JLEIC

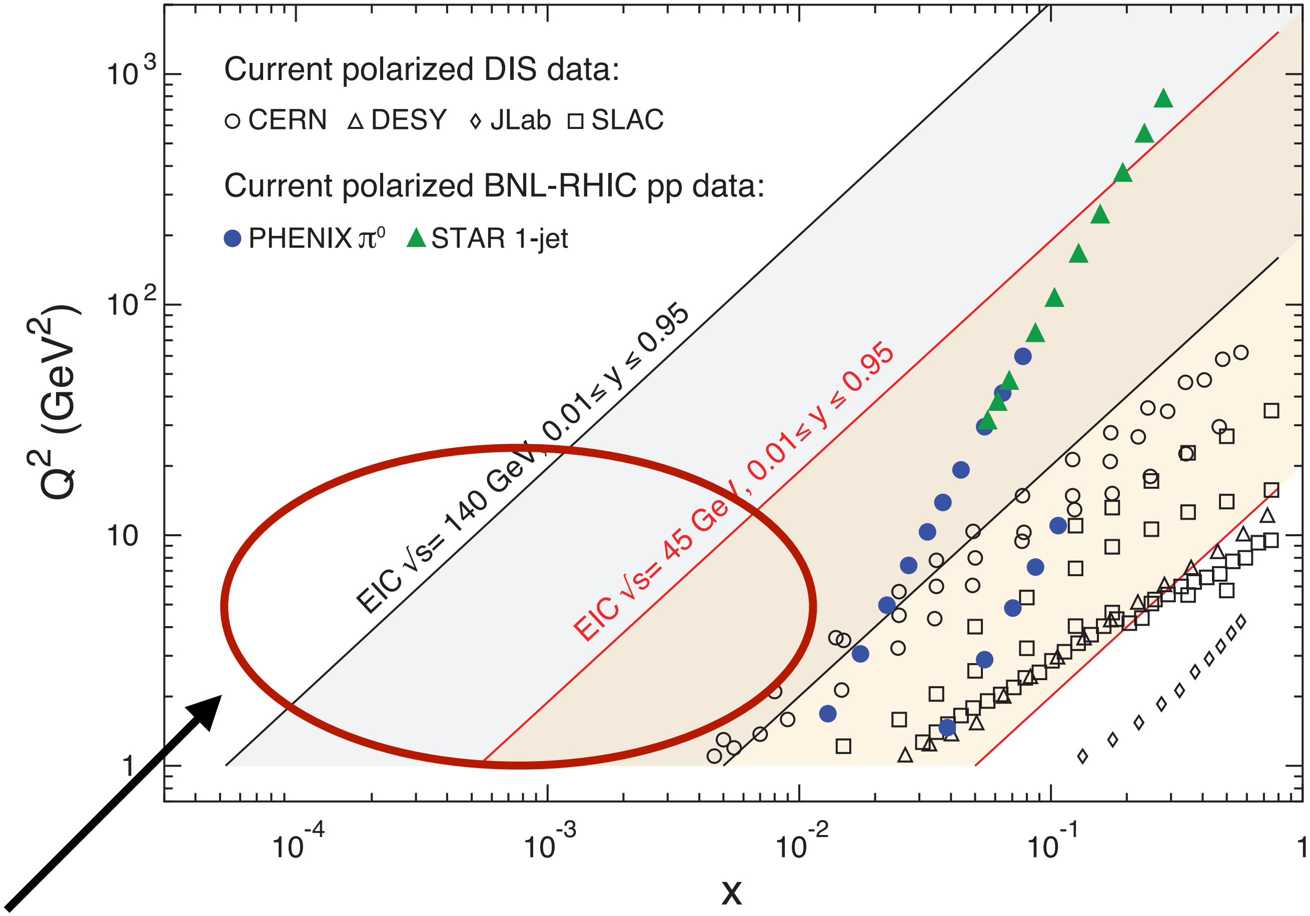


eRHIC



Main EIC parameters: polarization

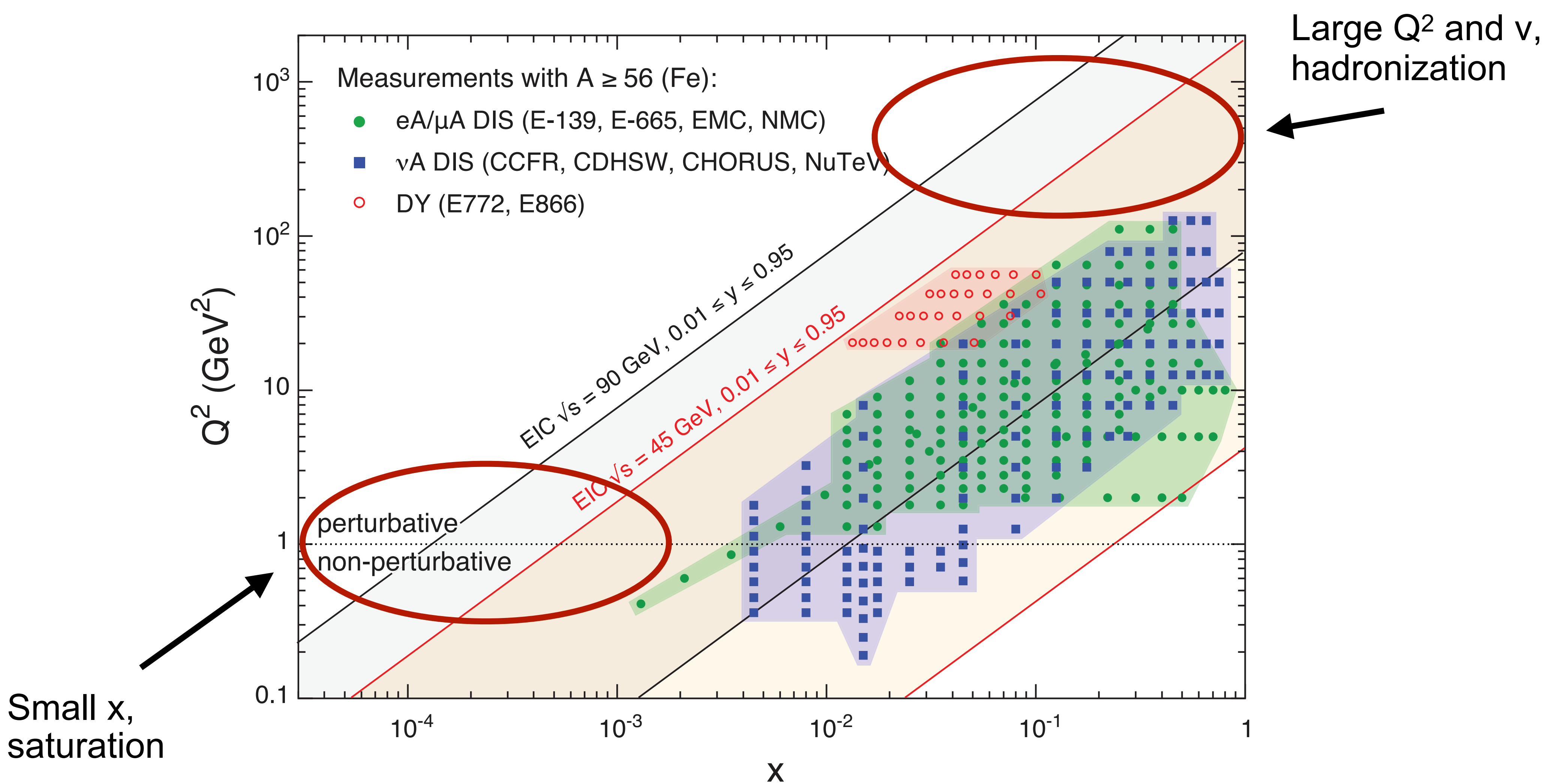
- High degree of polarization ~70% of beams of electrons, protons, light nuclei (D, He-3) → polarized DIS, 3D parton distributions from semi-inclusive (TMDs) and exclusive processes (GPDs).



- Wide region of Q^2 and small x in polarized DIS → determination of the gluon contribution ΔG to the proton spin.

Main EIC parameters: nuclei

- Acceleration of light (D, He-3) and heavy (U, Pb) nuclei → **for the first time nuclear DIS at a collider** → quark and gluon nuclear densities at small x, search for possible saturation of the gluon density.

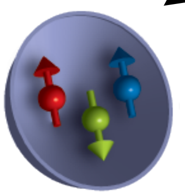


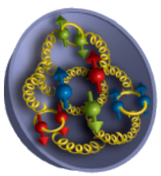
Key experiments: gluon polarization

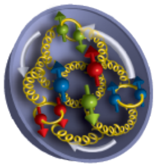
- Proton spin in QCD:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Orbital angular momentum of partons: unknown, access via GPD and TMD calculations in lattice QCD







Quark polarization:
measured well with fixed targets

$$\frac{1}{2}\sum_{q=u,d,s}\int dx(\Delta q(x) + \Delta\bar{q}(x)) \sim 30\%$$

→ "spin crisis".

Gluon polarizarion: RHIC spin physics, large uncertainty due to small-x region contribution

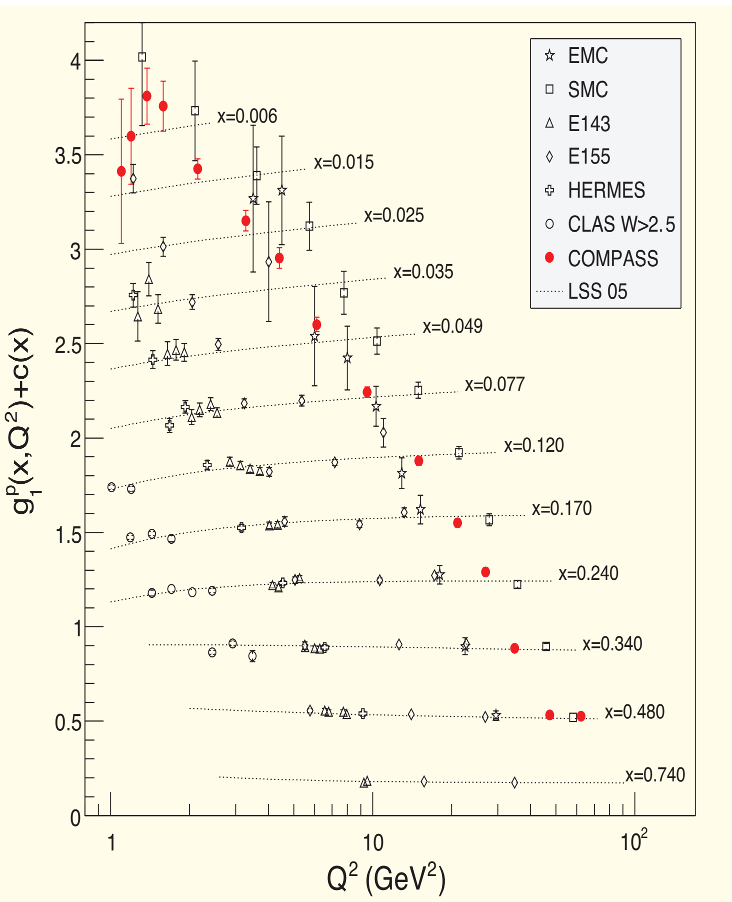
$$\Delta G = \int_{x_{min}}^{x_{max}} dx \Delta g(x) \sim 0 \pm 20\%$$

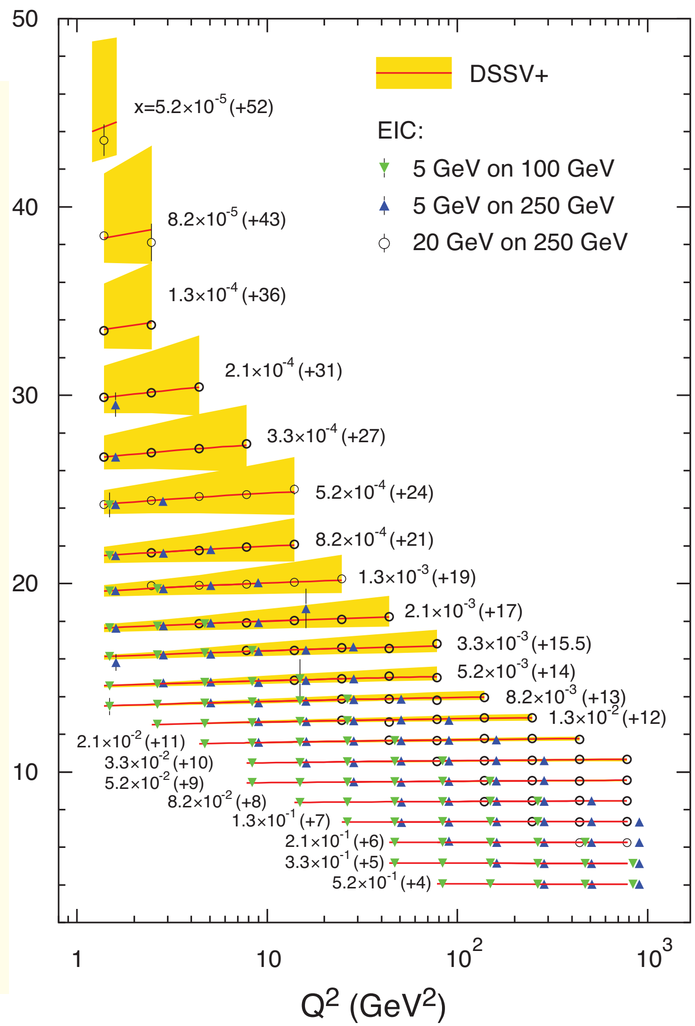
Key experiments: gluon polarization (2)

- Measurement of proton spin-dependent structure function $g_1^p(x,Q^2)$ and extraction of $\Delta g(x)$ using scaling violations:

EIC $\rightarrow$ $$\frac{dg_1^p(x,Q^2)}{d\log Q^2} \propto -\Delta g(x,Q^2)$$

World data





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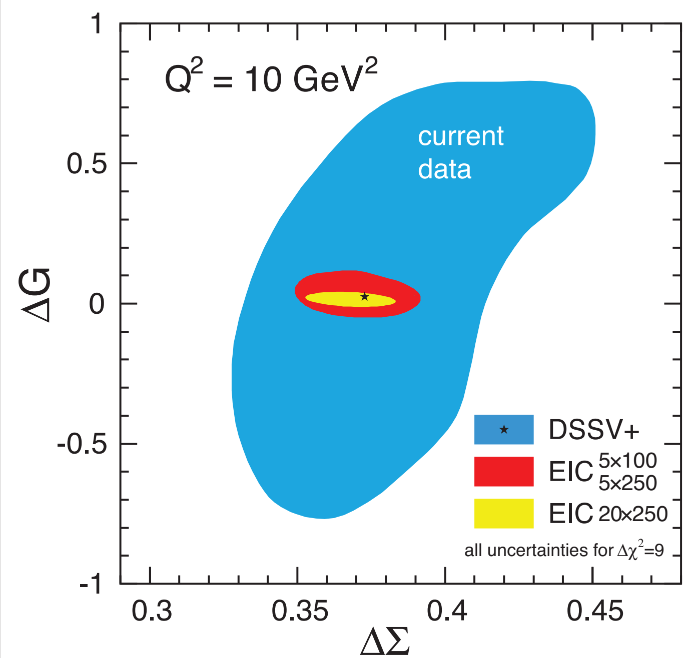
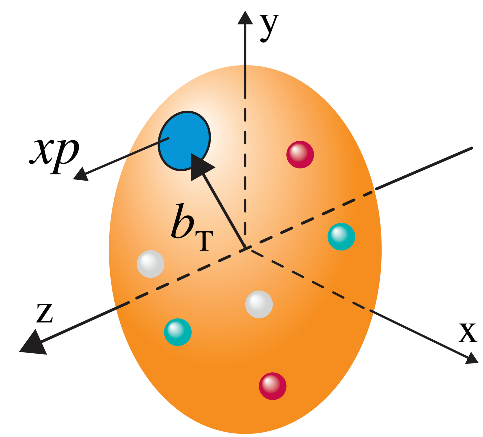
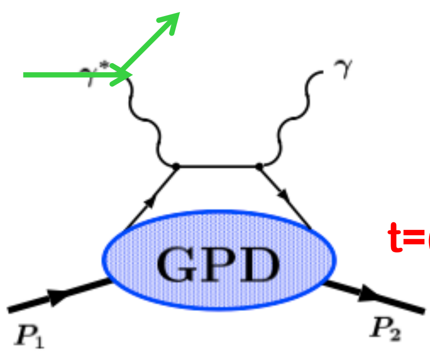


Key experiments: 3D parton distributions

- Determination of 3D parton distributions requires two scales: large Q^2 for parton localization and small (t, kT) for distances O(fm).

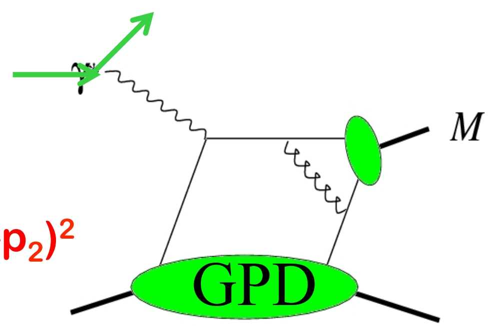
- Examples: hard exclusive processes, hybrid between inclusive and elastic scattering





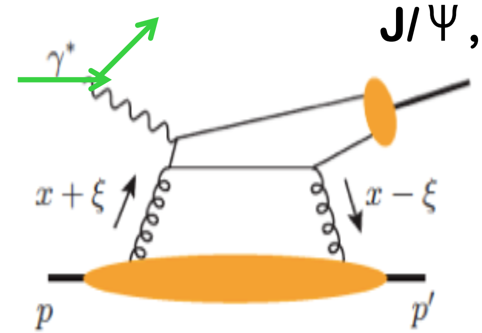
DVCS: $Q^2 >> |t|$

\+ $t=(p_1-p_2)^2$



DVEM: $Q^2 >> |t|$

\+ J/Ψ, Φ, ...



EHMP: $Q^2 >> |t|$

\+ ...

Deeply virtual Compton scattering (DVCS)

Deeply virtual meson production (DVMP)

- Fourier transformation w/respect momentum transfer *t* gives b_T-dependence.

Key experiments: 3D parton distributions (3)

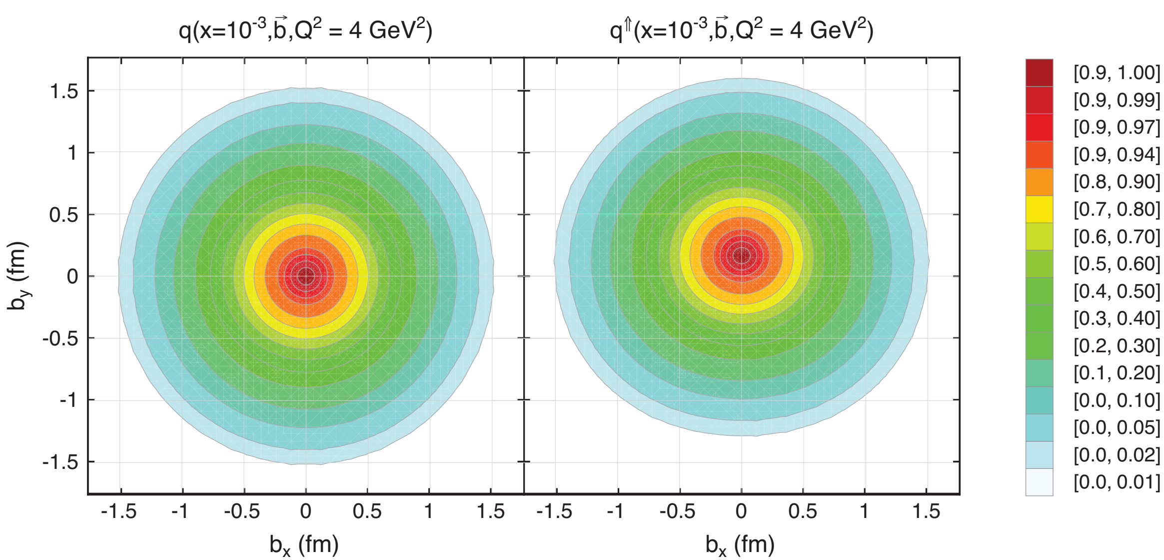
- Cross sections are expressed in terms of generalized parton distributions (GPDs), encoding QCD tomography of the target.
- GPDs are important for resolution of the proton “spin crisis”:

$$J^q = \frac{1}{2}\int dx\, x[H^q(x,\xi,t=0)+E^q(x,\xi,t=0)] = \frac{1}{2}\Delta q + L_q$$

- GPDs contain information on sheer forces experienced by partons in proton/ nuclei and also possible non-nucleonic degrees of freedom in nuclei.

- In the case of transversely-polarized target, b_T-dependence of GPDs depends on spin-orbit correlations (like in Sivers effect):

$$f^{\Uparrow}(x,\boldsymbol{b}_T) = f(x,\boldsymbol{b}_T^2) + \frac{(\boldsymbol{S}_T\times\boldsymbol{b}_T)^z}{M}\frac{\partial}{\partial \boldsymbol{b}_T^2}\, e(x,\boldsymbol{b}_T^2)$$



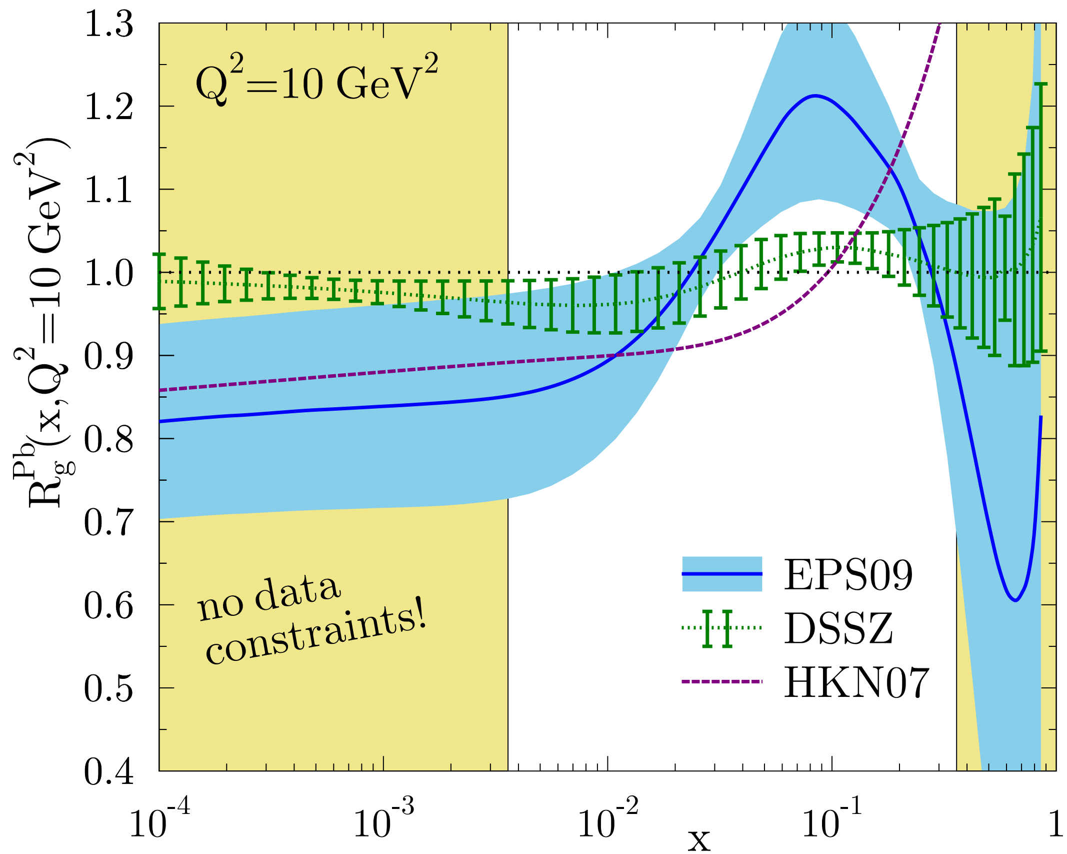
Key experiments: nuclear gluon distribution

- Nuclear gluon distribution $g_A(x,\mu^2)$ = density of gluons in nuclei as function of momentum fraction x at resolution μ, necessary input for phenomenology of hard processes with nuclei at high energies (RHIC, LHC).

$$R_g(x,Q^2) = \frac{g_A(x,Q^2)}{A g_p(x,Q^2)}$$

- $g_A(x,\mu^2)$ is known from available data with significant uncertainties (fixed-target DIS , dA@RHIC, pA@LHC) due to:

- limited range of energies, Q^2 and x
- indirect determination using scaling violation (Q^2 dependence $F_{2A}(x,Q^2)$)



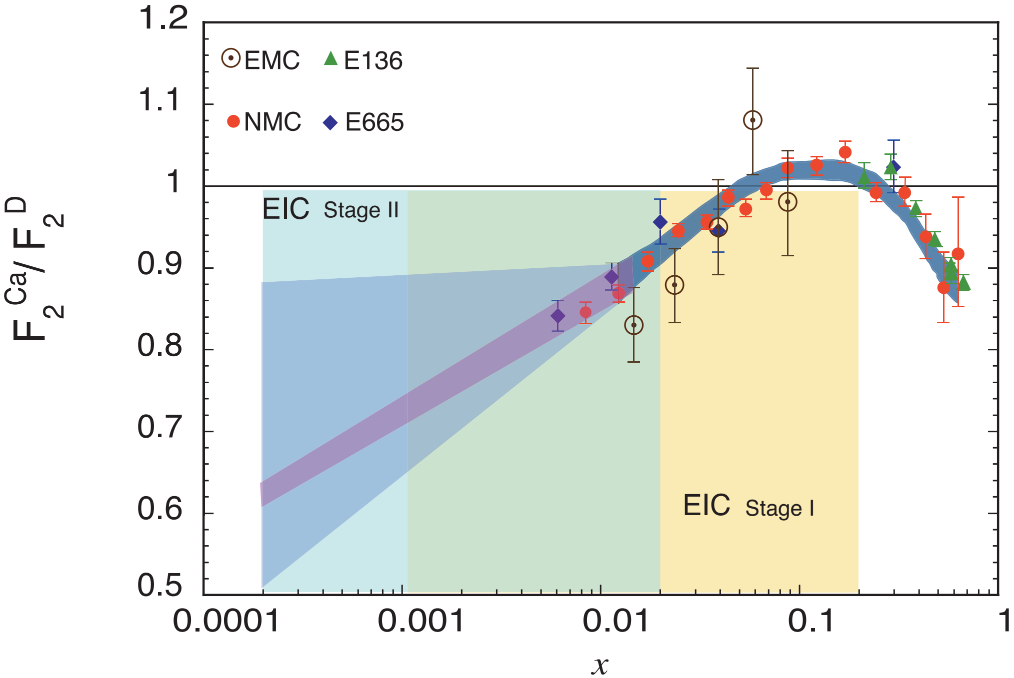
Key experiments: nuclear gluon distribution (2)

- High and *variable* energies at EIC will allow one to measure the nuclear structure functions $F_{2A}(x,Q^2)$ and $F_{LA}(x,Q^2)$ in a wide range of x, Q^2 - “first-day measurement”

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right) F_2(x,Q^2) - \frac{y^2}{2} F_L(x,Q^2)\right]$$

- Longitudinal structure function $F_{LA}(x,Q^2)$ directly probes $g_A(x,\mu^2)$.

$$F_L(x,Q^2) = \frac{2\alpha_s(Q^2)}{\pi}\int_x^1 \frac{dy}{y}\left(\frac{x}{y}\right)^2 \sum_q^{n_f} e_q^2\left[\left(1-\frac{x}{y}\right) yg(y,Q^2) + \frac{2}{3}\left(q(x,Q^2)+\bar{q}(x,Q^2)\right)\right]$$



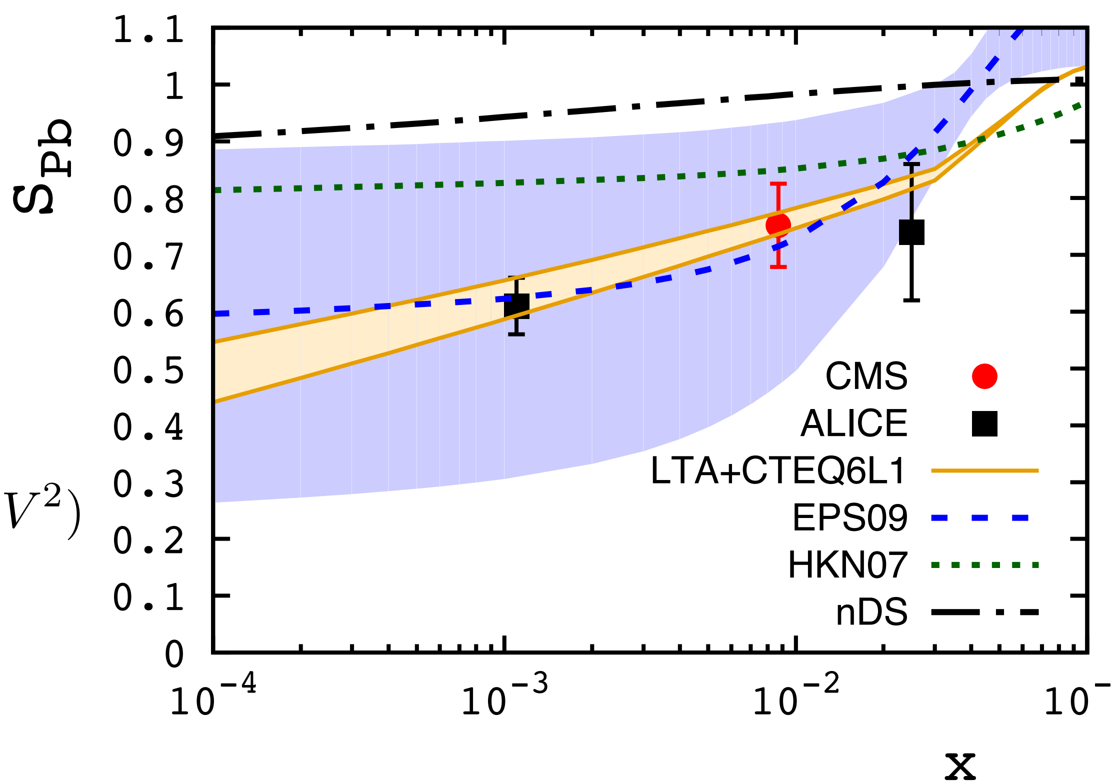
Nuclear gluon density from J/ψ photoproduction on nuclei at the LHC

• Before EIC, new constraints on $g_A(x,\mu^2)$ at small x were obtained by analyzing the data on coherent photoproduction J/ψ on nuclei in Pb-Pb ultreperipheral collisions (UPCs), Guzey Zhalov, Kryshen, Strikman, 2012-2017

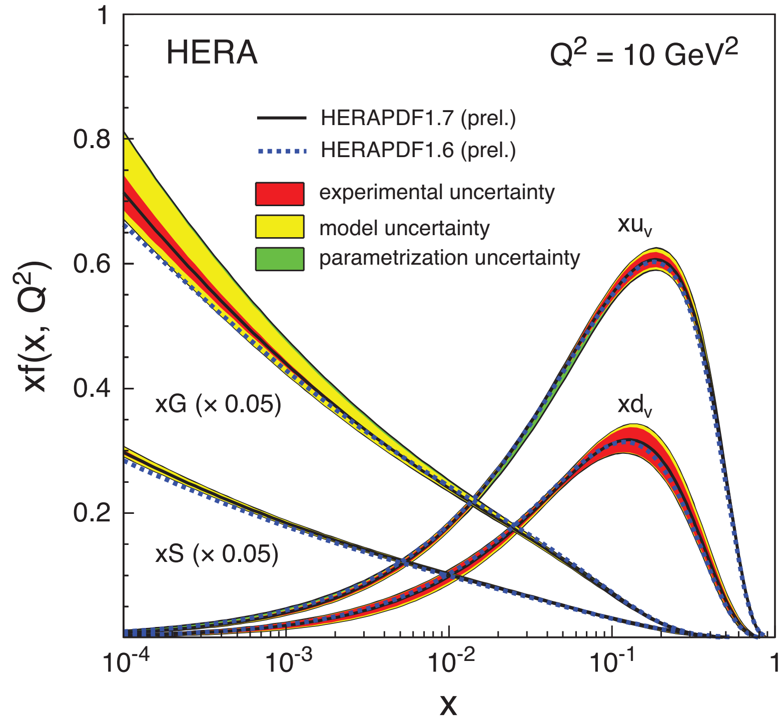
• The cross section is proportional to the gluon density squared → the ratio of cross sections of the nucleus/proton = factor of nuclear modification/ suppression of $g_A(x,\mu^2)$.

$$S(W_{\gamma p}) \equiv \left[\frac{\sigma^{\exp}_{\gamma Pb\to J/\psi Pb}(W_{\gamma p})}{\sigma^{\rm IA}_{\gamma Pb\to J/\psi Pb}(W_{\gamma p})}\right]^{1/2}$$

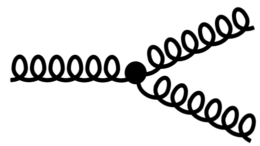
$$S_{Pb}(W_{\gamma p}) = R_g(x = \frac{M^2_{J/\psi}}{W^2_{\gamma p}}, Q^2 = 3\ GeV^2)$$



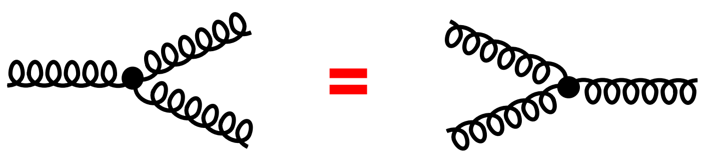
Key experiments: gluon saturation



- As the collision energy increases (x decreases) the gluon density increases due to gluon radiation (DGLAP, BFKL):



- At some point, radiation is compensated by recombination → saturation



at Q_s

- A new dynamical saturation scale Qs from the estimate $\rho \times \sigma_{gg \to g} \sim 1$

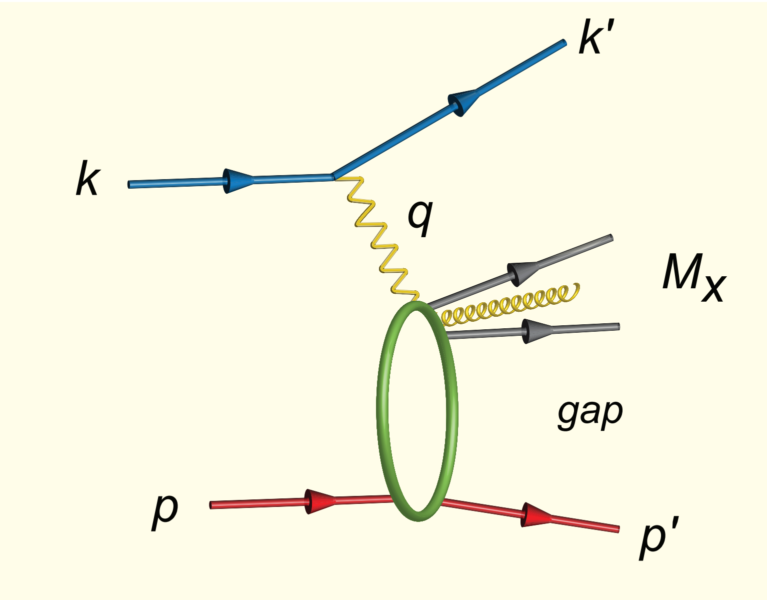
$$Q_s^2 \sim \frac{\alpha_s x G_A(x, Q_s^2)}{\pi R_A^2} \sim A^{1/3} \frac{1}{x^{0.3}}$$

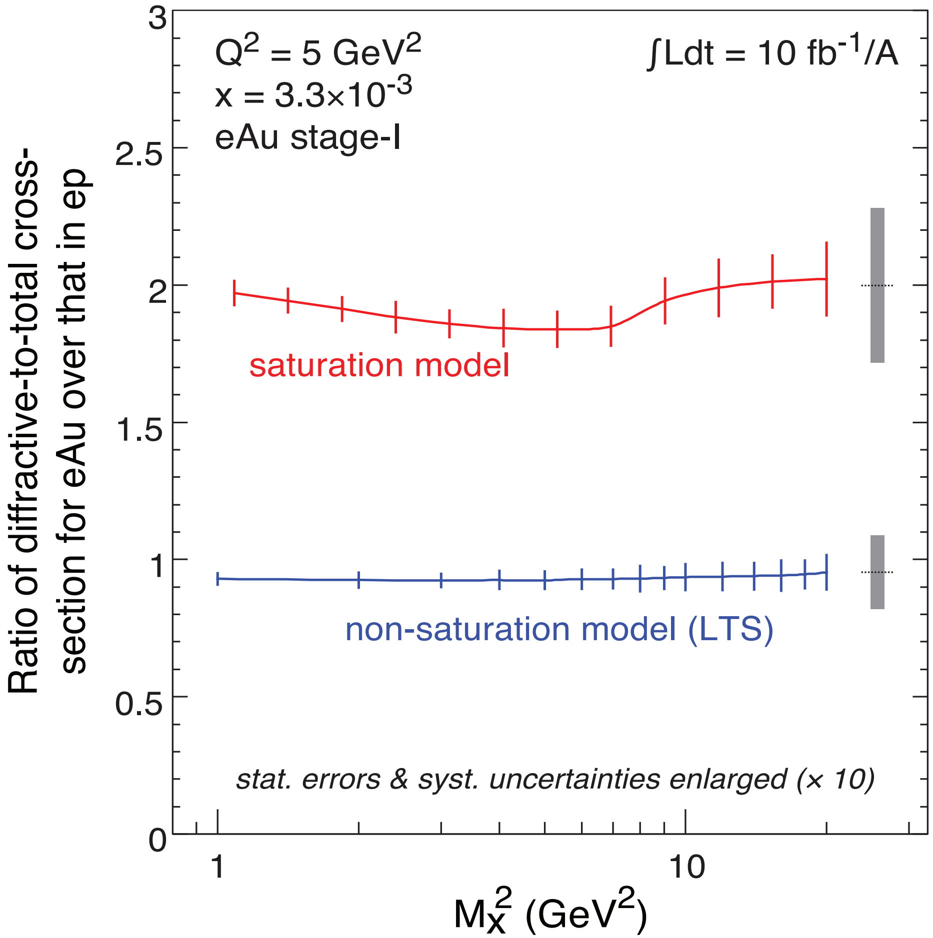
- Nuclear enhancement of Qs is a kew factor for EIC!

Key experiments: gluon saturation (2)

- The regime of gluon saturation was theoretically predicted in the color glass condensate (CGC) framework.
- Despite may successful phenomenological applications at RHIC and LHC, there is no convincing evidence of onset of this new regime of low-x QCD.
- At EIC, it is proposed to look for saturation by studying inclusive, diffractive and exclusive DIS.

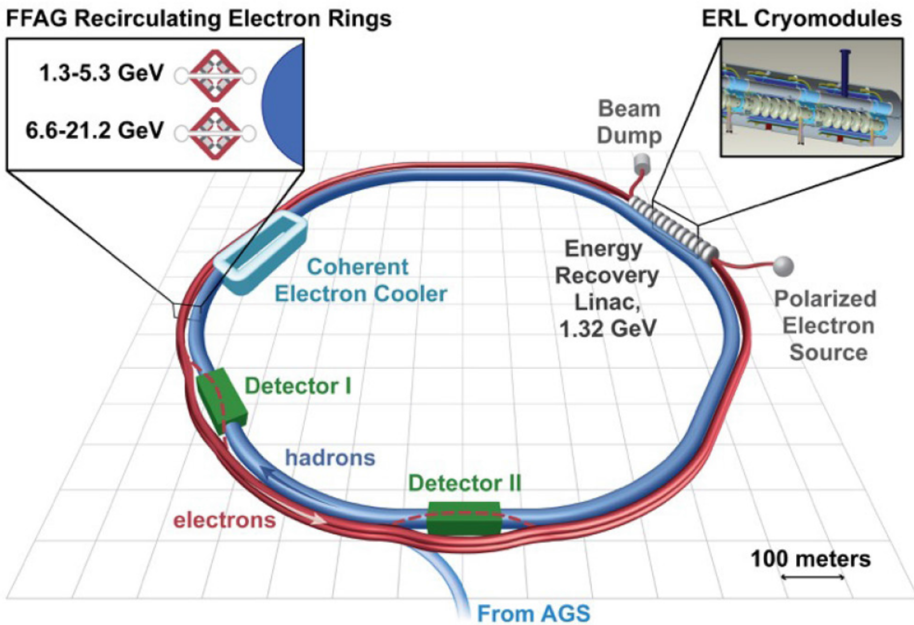
Diffractive DIS





Realization of EIC: eRHIC vs. JLEIC

BNL design



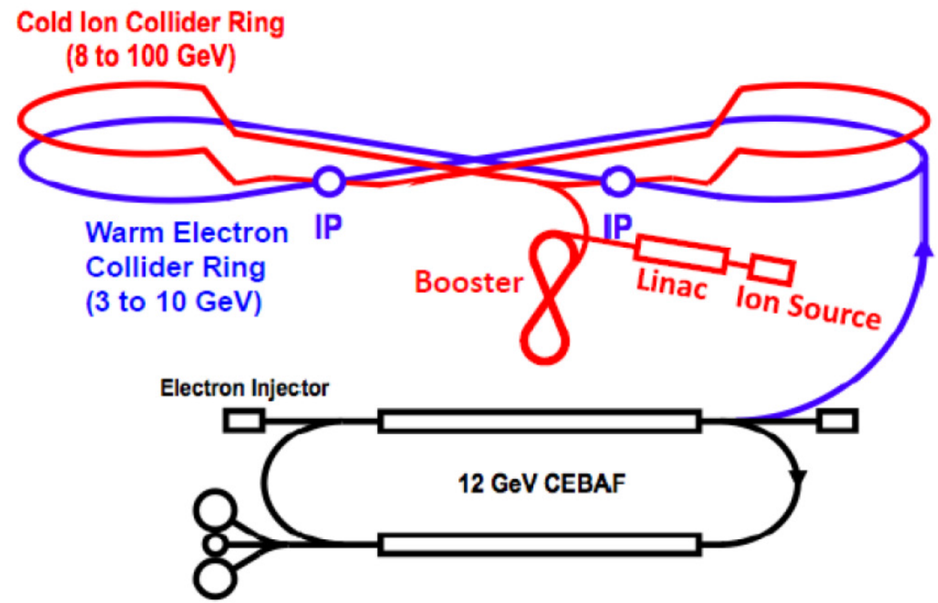
- 5-10 GeV electron ring (upgradable to 20-30 GeV)
- 50-250 GeV proton/ion

$Q^2 = x.y.s$

NSAC long range plan (2015)

Emphasis on high energy

JLab design

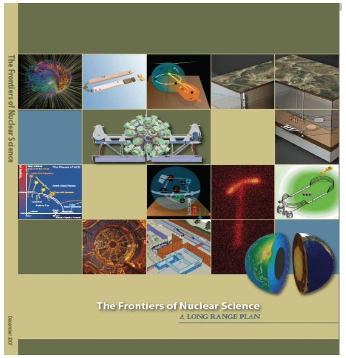


- 3-10 GeV electron ring
  10-100 GeV proton/ion

Various CM energies possible.
Example: 10 GeV e on 100 GeV p - CM energy of ~60 GeV

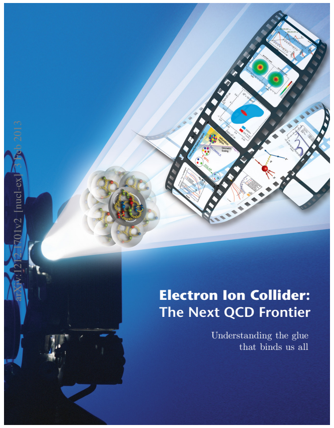
Emphasis on high luminosity

A U.S-based EIC: status



- 2007 NSAC Long Range Plan: recommendation to develop a conceptual of the accelerator and detector guided by the physics program

- 2010: 10-week INT program (Seattle, USA) “Gluons and quark sea at high energies”, arXiv:1108.1713



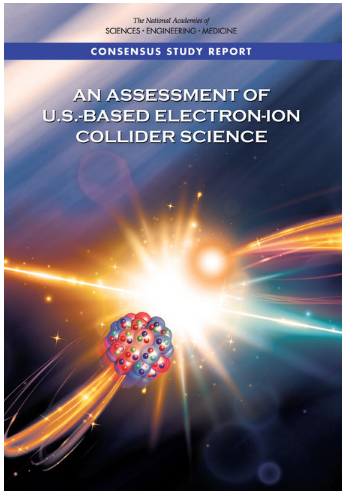
- 2013: EIC White Paper, arXiv:1212.1701, EPJ A52 (2016) 268

- 2015 NSAC Long Range Plan:

“We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.”

- 2017 assessment of NAS: Full support.

“An EIC is timely and has the support of the nuclear science community. The science that it will achieve is unique and world leading…”



EIC: organization

- EIC working groups at BNL, https://wiki.bnl.gov/eic/ and JLab, https://eic.jlab.org/wiki/index.php/Main_Page

- Electron-Ion Collider User Group since 2016: > 800 scientists from > 170 institutes and universities, http://www.eicug.org/web/

- Yearly POETIC (Physics Opportunities at an Electron-Ion Collider) conferences. Latest one in Regensburg (Germany), https://indico.cern.ch/event/663878/

- EIC talks at all major particle and nuclear physics conferences.

Summary

- High-energy and high-luminosity polarized EIC is viewed as a key facility to study fundamental questions of QCD.

- The main aim of the EIC physics program is to understand the microscopic nature of the visible matter in the language of quarks and gluons of QCD.

- In particular, it is planned to study:
  - the spin- and 3D-structure of the proton
  - the role of nuclear matter in the distribution of quarks and gluons
  - propagation of color charges (hadronization)
  - possible onset of a new regime of high-density saturated gluonic matter.

- EIC has full support of the U.S. nuclear physics community. Next steps is to obtain CD0 ("Mission Need" statement, expected in 2018) and CD1 (design choice and site selection, expected in 2019).